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ELECTRICAL IMPEDANCE OF THE HUMAN BODY

Herman P. Schwan

U.S. NAVAL WEAPONS LABORATORY
DAHLGREN, VIRGINIA

NWL

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U. S. NAVAL WEAPONS LABORATORY

Dahlgren, Virginia

22448

John D. Chase, Capt., USN
Commander

Bernard Smith
Technical Director

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by

Herman P. Schwan

Weapons Development and Evaluation Laboratory

ABSTRACT

The object of this report is to establish the theoretical range of radio frequency impedance of the human body in the 1 - 30 MHz range. The report defines whole body rf impedance, summarized available specific tissue impedance data, and predicts likely values of total body impedance for various electrode sizes and locations from known specific tissue data and skin impedance. The report also discusses the relation of body impedance to electrode impedance, skin impedance and specific body impedance.

FOREWORD

During handling and loading of electrically initiated ordnance in an electromagnetic environment, the human crew member may become a significant part of an rf path through which the ordnance may be unintentionally fired.

To better understand the part which the human crew member contributes to the overall problem of Hazards of Electromagnetic Energy to Ordnance (HERO), The Engineering Studies Group of the Weapons Development and Evaluation Laboratory has been assigned the task of determining the rf impedance of the human body in the frequency range of primary interest (2 - 30 MHz).

This report is a theoretical study of the problem which was conducted by Dr. Herman P. Schwan, Head of the Department of Biomedical Electronic Engineering, University of Pennsylvania, Philadelphia, Pennsylvania while he was employed by the U. S. Naval Weapons Laboratory.

Released by:

D. W. Stoner

D. W. STONER, Director
Weapons Development and
Evaluation Laboratory

CONTENTS

I. INTRODUCTION

A considerable body of specific tissue impedance data is available in the literature. A complete knowledge and understanding of the tissue impedance's frequency dependence has been achieved over the total frequency range from 1 cps to several thousand megahertz. On the other hand there exist only very few whole body impedance data. This is most surprising since total body impedance data are a necessary prerequisite to any understanding of electrical hazards to mankind arising from contact with low frequency and radio frequency voltages. They are also of interest in several electrical diagnostic and therapeutic techniques.

It is the purpose of this report

A. To summarize available specific impedance data

B. To define body impedance and to relate it to electrode impedance, skin impedance and specific body impedance data

C. To predict likely values of total body impedance for various electrode sizes and locations from known specific tissue impedance data and skin impedances.

Of primary interest here will be body impedance values in the radio frequency range from 1-30 MHz.

II. SPECIFIC BODY IMPEDANCE DATA

The electrical properties of tissues and of matter in general are uniquely characterized by their dielectric constant ε relative to air and conductivity κ. These data relate to the capacitance C (in Farad) and conductance G (in Mho) of a tissue sample as follows:

$$C = \varepsilon\varepsilon_o \frac{A}{d} \qquad (1)$$

$$G = \kappa \frac{A}{d} \qquad (2)$$

where ε_o is the capacitance of a unit volume of free space and equal to 8.84×10^{-14} Farad cm^{-1} and where d (in cm) and A (in cm^2) are the electrode separation and cross section of the sample.

Equations (1) and (2) assume a uniform current field as achieved if the sample is confined by a cylinder as indicated in Figure 1, and neglect the possible existence of additional stray field contributions C_s outside the cylindrical tissue volume. The Figure 1b indicates how such stray fields contribute: One stray field contribution from

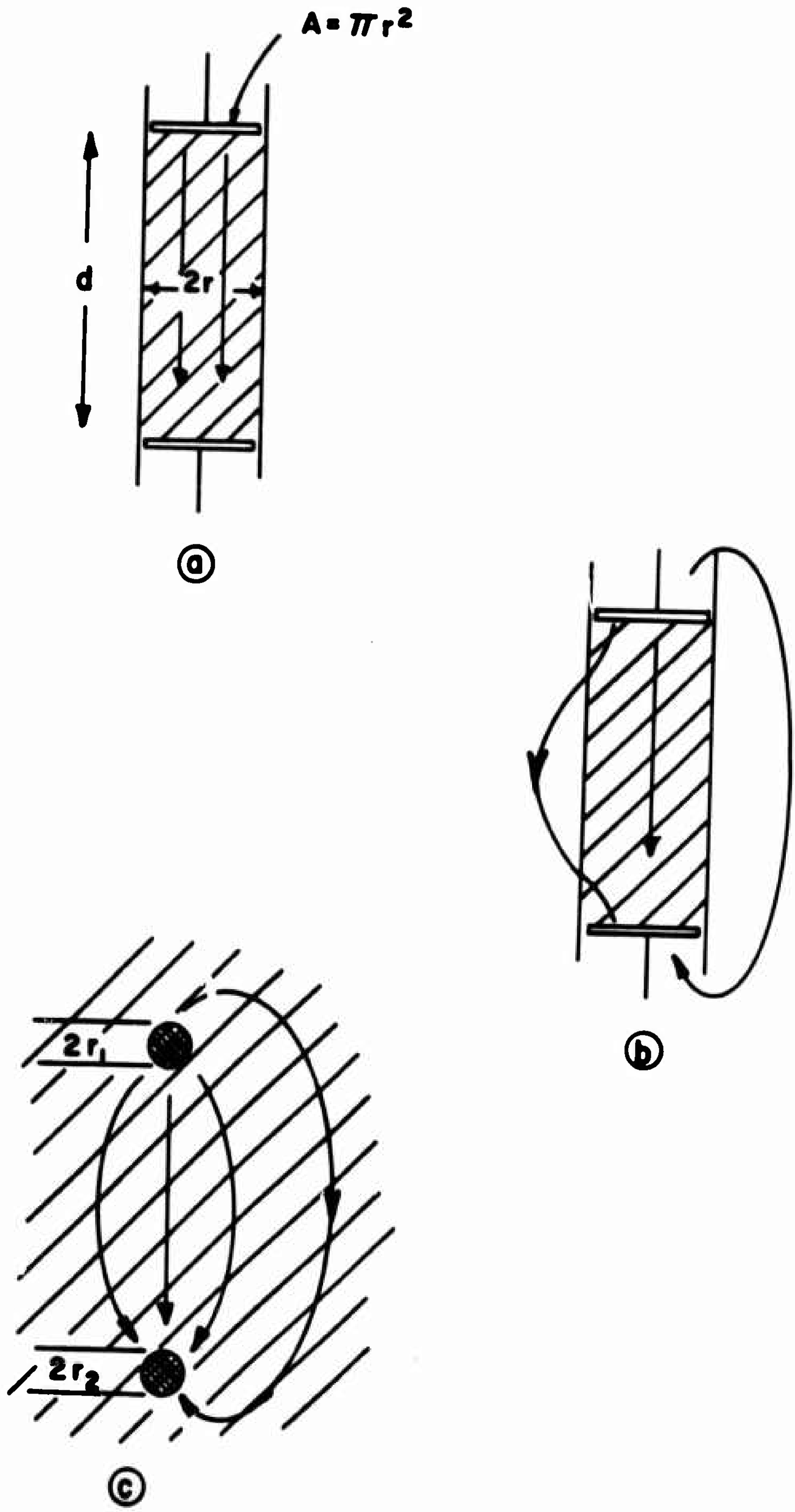

FIG. 1

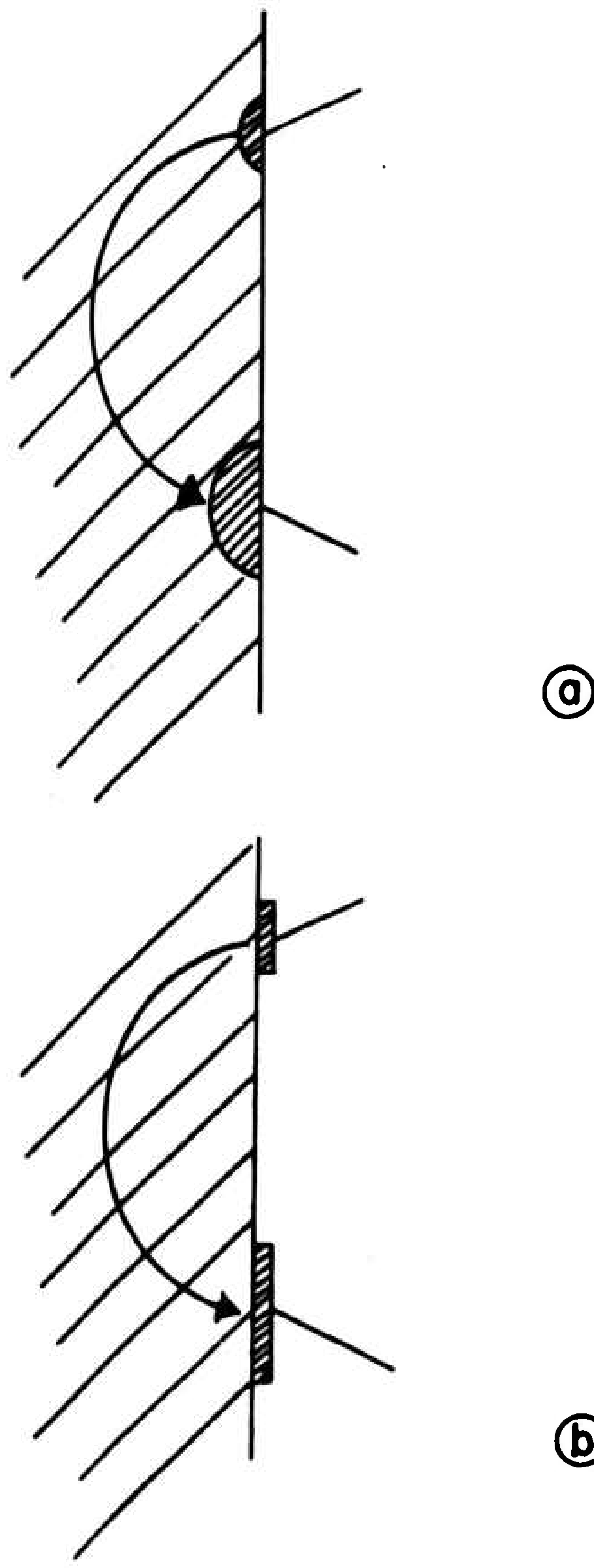

FIG. 2

the back of the electrodes establishes a simple additive contribution to the tissue capacitance. However, another arises from the fact that part of the current passes partially through the tissue, then through the walls of the tissue confining cell into the medium outside of the cell, usually air, and eventually back through the tissue. This contribution depends both on C and G of the tissue's sample, and is difficult to assess. Fortunately, the contribution of stray fields to total observed tissue capacitance values is usually small at frequencies up to several megahertz provided that the cell radius r is not too small compared with d. This is due to the fact that ε ranges from about one hundred to many thousand and the C-values given by (1) are therefore much greater than stray field contributions.

If spherical electrodes of radii r_1 and r_2 are completely surrounded by tissue as depicted in Figure 1c, the equations (1) and (2) are to be replaced by the equations

$$C = \varepsilon\varepsilon_o/K \tag{3}$$

$$G = \kappa/K \tag{4}$$

where the cell constant K is given by

$$K = \frac{1}{4\pi}\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{5}$$

This case is of particular interest to us since, from symmetry, it directly relates to the electrode geometry shown in Figure 2a. Here a half spherical electrode arrangement is assumed. For this case

$$K = \frac{1}{2\pi}\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{6}$$

The arrangement 2a approximates the situation which exists if two simple disk electrodes, Figure 2b, are attached to the human body. The impedance observed with the arrangement 2b is usually fairly close to that in 2a if the electrode areas of the disks are made equal to those of the half spheres in 2a.

The specific admittance of body tissues is defined by the admittance of a volume unit of tissue

$$Y_s = \kappa + j\omega\varepsilon\varepsilon_o \tag{7}$$

Its inverse is the specific tissue impedance

$$Z_s = \frac{1}{\kappa + j\omega\varepsilon\varepsilon_o} \tag{8}$$

Thus specific admittance and impedance are complex quantities and defined in terms of ε and κ. The magnetic properties of tissues are of no interest here. They are trivial, the permeability being equal to or very close to that of free space and the magnetic losses negligible. At frequencies below 100 MHz, the ratio $\tan\delta = \kappa/\omega\varepsilon\varepsilon_o$ is usually significantly higher than two as demonstrated in Figure 4. Since the magnitude of Z_s is taken from equation (8) to be

$$|Z_s| = \frac{1}{\kappa} \quad \frac{1}{\sqrt{1 + 1/\tan^2\delta}} \tag{9}$$

it is therefore permissable to approximate equation (9) by

$$|Z_s| = \frac{1}{\kappa} = \rho \tag{10}$$

where ρ is the specific resistance. This approximation gives the magnitude of Z_s accurate to about 10% or less.

A survey of ε and $\rho = 1/\kappa$ data for tissues in the radio frequency range is given in the older literature (Rajewsky et al, 1938). Values at low frequencies have been given by Schwan and Kay (1956, 1957) and values in the high frequency range by Herrick (1950), Osswald (1937) and Schwan and Li (1953). A detailed discussion of these and other data and of the reasons why their values are such as observed is given by Schwan (1957). A summary of all these and other pertinent data is given in the following Table 1. More detailed data in the high frequency range are presented in Table 2 and Figure 3.

However, most of the material in these tables has been obtained on excised tissues. At frequencies below 100 KHz the specific resistance of blood is rather low in comparison with that of tissues given in the tables and electrical currents will tend to take advantage of the presence of blood. Thus under live conditions, actual specific impedance data of tissues supplied with blood can be anticipated to be somewhat lower below 100 KHz than quoted in Table 1. At frequencies in excess of 100 KHz the difference in blood and tissues specific resistance becomes less pronounced and blood's influence on the tissue impedance should be less noticeable.

Several conclusions can be drawn from the data:

A. All tissues can be divided into several major classes including tissues with high water such as muscle and all body organs and tissues of low water content such as bone and fat. Brain and lung

TABLE 1.

Alternating current properties of body tissues

The tables include a) ranges of values as quoted, b) averages of values and c) single values, characteristic for a single sample of tissue. The values, falling under the category a) give a more comprehensive idea of the variability involved. The values pertaining to single samples characterize best the frequency dependence and have been chosen for this purpose.

A. Specific resistance (Ohm cm.)

	Frequency	A Muscle	B Liver	C Lung*	D Spleen	E Kidney	F Brain	G Fatty tissue	H Bone and bone marrow	I Whole blood
1										166
2	100 cps		1000							
3										
4		800	800	1000				1500—5000		166
5	1 Kc		970	400—850				1700—2500		147
6		980	700—1300		280—430		450—550			130—180
7										
8	10 Kc		850							147
9		880								
10			480							
11	100 Kc	170—250	220—550	165—200	250—500	150—270	480—850			147
12		520	550—800							
13										
14	1 Mc	160—210	210—420	150—180	230—380	140—250	430—700			140
15		250	400—550							
16										
17	10 Mc	150—170	180—260	110—150	150—170	120—170	300—450			90
18										
19		100—130	120—145	95—130	85—105	100—120	180—230	1170—1250		82
20	100 Mc	120—[illegible]	150—200	100—140	110—150	100—150	200—300	1500		
21		140—200	180—210		180	130—180	220—280	2200—4300	4100—5300	120—150
22		75—79	98—106					700—1400	1000—2300	64—72
23	1,000 Mc	81—84	92—100	137		81—82		1100—3500		80
24		77	100					2500		
25		12	15—17					240—370	60—200	11
26	10,000 Mc	13						210	100—130	9.5

Temperature coefficient of specific resistance: —2%/° C. whenever frequency dependence is very small. Complicated function of frequency, but always above —2%/° C. when frequency dependence is pronounced.

B. Dielectric constant

1		$800 \cdot 10^3$	$900 \cdot 10^3$	$450 \cdot 10^3$				$150 \cdot 10^3$		
2	100 cps	$1000 \cdot 10^3$								
3										
4		$120 \cdot 10^3$	$150 \cdot 10^3$	$90 \cdot 10^3$				$80 \cdot 10^3$		
5	1 Kc	$170 \cdot 10^3$								2900
6		$100 \cdot 10^3$								
7		$80 \cdot 10^3$	$50 \cdot 10^3$	$30 \cdot 10^3$				$20 \cdot 10^3$		
8	10 Kc	$90 \cdot 10^3$								2810
9		$80 \cdot 10^3$								
10										
11	100 Kc	$30 \cdot 10^3$								2740
12		$20 \cdot 10^3$	$(7-12) \cdot 10^3$							
13										
14	1 Mc									2040
15		$2 \cdot 10^3$	$(12-2) \cdot 10^3$							
16										
17	10 Mc									200
18										
19			65—75					8—13		
20	100 Mc									
21		60—73	72—74		88—90	83—84	70—75			72—74
22		49—52	46—47					4.2—7.8	4.2—7.8	58—62
23	1,000 Mc	53—55	44—52	35		53—56		3.2—6		63
24		61	50					9.5		
25		40—42	34—38					3.5—3.9	4.4—6.6	50—52
26	10,000 Mc	29						3.6	6	45

Temperature coefficient of dielectric constant. Smaller than 0.5% when frequency dependence is very small. Positive, but complicated function of frequency when frequency dependence is pronounced.

* Partially or totally deflated, except material reference [1].

Table 1 (Continued)

Data		Data		Data	
Coordinates	References	Coordinates	References	Coordinates	References
1 *A*—*C*, *G*	[*1*]	6 *I*	[*16*]	14 *A*—*F*	[*4*]
1 *I*	[*3*]	7 *A*—*C*, *G*	[*1*]	14 *I*	[*6*]
2 *A*	[*2*]	8 *A*	[*2*]	15 *A*	[*7*]
2 *B*	[*1*]	8 *B*	[*1*]	15 *B*	[*8*, *9*]
4 *A*—*C*, *G*	[*1*]	8 *I*	[*6*]	17 *A*—*F*	[*4*]
4 *I*	[*3*]	9 *A*	[*7*]	17 *I*	[*6*]
5 *A*	[*2*]	10 *B*	[*1*]	19 *A*—*G*, *I*	[*10*, *11*]
5 *B*	[*1*]	11 *A*—*F* (Resist.)	[*4*]	20 *A*—*G*	[*4*]
5 *C*, *G*	[*5*]	11 *A* (Diel. const.)	[*2*]	21 *A*, *B*, *D*—*I*	[*12*]
5 *I*	[*6*]	11 *I*	[*6*]	22 *A*, *B*, *G*—*I*	[*13*]
6 *A*	[*7*]	12 *A*	[*7*]	23 *A*—*C*, *E*, *G*, *I*	[*14*]
6 *B*, *D*, *F*	[*8*, *9*]	12 *B*	[*8*, *9*]	24 *A*, *B*, *G*	[*17*]
				25 *A*, *B*, *G*—*I*	[*13*]
				26 *A*, *G*, *H*, *I*	[*15*]

References pertain to material as stated:

[*1*] Dog, in situ at 37° C. [*2*] Frog, excised piece at 25° C. [*3*] Sheep, at 18° C. [*4*] Human, minced material at 23° C. [*5*] Dog, in situ at 37° C. [*6*] Rabbit, at room temperature. [*7*] Rabbit, excised piece at room temperature. [*8*] and [*9*] Human and various animals, excised pieces and minced material at 23° C. [*10*] and [*11*] Human, minced at 37° C. (except blood, 20° C.) [*12*] Beef and pork, excised at 20° C. [*13*] Dog and horse, excised at 38° C. (except bone and bone marrow, 25° C.) [*14*] Human, excised piece at 27° C. [*15*] Human, excised piece at 37° C. [*16*] Sheep, at 18° C. [*17*] Beef, minced at 22° C. [*18*] Human, blood at 6—34° C. [*19*] Theoretical Analysis.

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[*1*] Schwan, H. P., and C. F. Kay: Circulat. Res. 4, 664 (1956); 5, 439 (1957).
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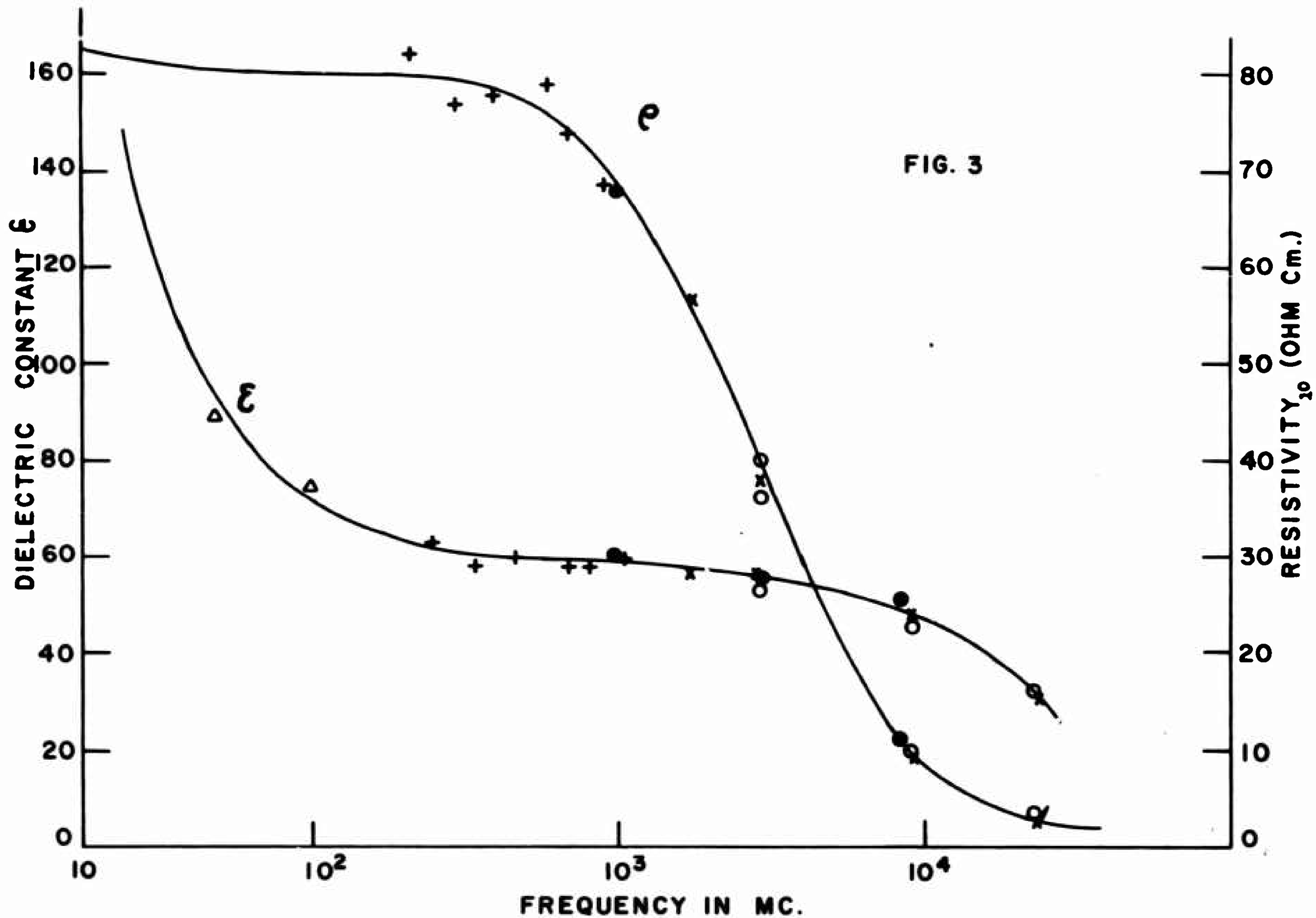
[*19*] — Ann. Physik 40 V, 509 (1941a).

TABLE 2. Dielectric constant and specific resistance of body tissues at 37° C

	Frequency								
	25 MHz	50 MHz	100 MHz	200 MHz	400 MHz	700 MHz	1000MHz	3000MHz	8500MHz
				Dielectric constant ϵ					
Muscle	103–115	85–97	71–76	56	52–54	52–53	49–52	45–48	40–42
Heart muscle				59–63	52–56	50–55			
Liver	136–138	88–93	76–79	50–56	44–51	42–51	46–47	42–43	34–38
Spleen	200	135–140	100–101						
Kidney	200	119–132	87–92	62	53–55	50–53			
Lung				35	35	34			
Skin			65		46–48		43–46	40–45	36
Brain	160	110–114	81–83						
Fat		11–13		4.5–7.5	4–7		5.3–7.5	3.9–7.2	3.5–4.5
Bone marrow		6.8–7.7					4.3–7.3	4.2–5.8	4.4–5.4
				Specific resistance ρ					
Muscle		113–147		95–105	85–90	73–79	75–79	43–46	12
Heart muscle				95–115	85–100	78–95			
Liver	185–210	173–195	154–179	110–150	105–130	85–115	98–106	49–50	15–17
Spleen		128–151							
Kidney		90–145		90	85	76–77			
Lung		260–450		160	140	130			
Skin			120–140		110–130		90–110	37–50	14
Brain	220	190–210	180–195						
Fat		1700–2500		1050–3500	900–2800		670–1200	440–900	240–370
Bone marrow		2800–5000					1000–2300	445–860	210–600

Figure 3. Specific resistance ρ and dielectric constant ε at 37°C between 10 and 20,000 MHz. Results were obtained by Osswald (Δ), Schwan and Li (+), Herrick et al (●), England (o)and Cook (x).



DIELECTRIC CONSTANT ε
RESISTIVITY$_{10}$ (OHM Cm.)
FREQUENCY IN MC.
ρ
ε

FIG. 3

take a somewhat intermediate position in this classification according to water content. Finally blood has a higher water content than any tissue and is, therefore, in a class by itself. The tissues with high water content have up to tenfold higher conductivity values and dielectric constants than fat and bone.

B. The conductive part of the specific admittance is always higher than the capacitive one. The ratio of these two currents is given by $1/\omega\epsilon\epsilon_o\rho$ and is shown in Figure 4 for two cases of high water content, muscle and blood. For frequencies up to 100 MHz, it is greater than two and, therefore, the magnitude of the tissue impedance simply given by equation (10). However, at frequencies in excess of 100 MHz, equation (9) or the equation (8) is more appropriate. Since we are in this study primarily interested in the radio frequency range, we can safely approximate the impedance magnitude by specific resistance values and neglect capacitive currents.

C. Tissues, which by the very nature of their cell membrane shape are anisotropic, also display anisotropic electrical properties. This is indicated in the Table 3 which includes data by Burger and van Dongen (1961) and Rush et al (1963). However, the electrical anisotropy decreases with frequency. Above 100 KHz tissue cell membranes appear virtually short circuited since the membrane reactance becomes small compared with the ionic pathways in series (Schwan, 1957). Hence the reason for the electrical anisotropy disappears and tissues display essentially isotropic electrical characteristics.

III. BODY IMPEDANCE CONSIDERATIONS

A. Electrode impedance

Electrode polarization phenomena take place at the interface between electrodes and a conducting medium such as body tissues. This electrode polarization results from the presence of boundary potentials between the electrode and the conducting medium. Details about electrode polarization will not be reviewed here, since covered in detail elswhere (Schwan, 1968). However, in the present context it is important to realize that an electrode polarization impedance element exists between the electrodes and the material in contact with them. This polarization impedance $Z_p = R_p + jX_p$ is highly frequency sensitive and has a reactive component which may be characterized by a polarization capacitance $C_p = 1/\omega X_p$ where the polarization capacitance C_p is assumed to be placed in series with the resistance. We can write

$$C_p = C_o f^{-m} \; ; \; R_p = R_o f^{-n} \tag{11}$$

and it is observed that approximately

$$\tan \delta = R_p \, \omega \, C_p \; ; \quad \delta = m \frac{\pi}{2} \tag{12}$$

FIG. 4

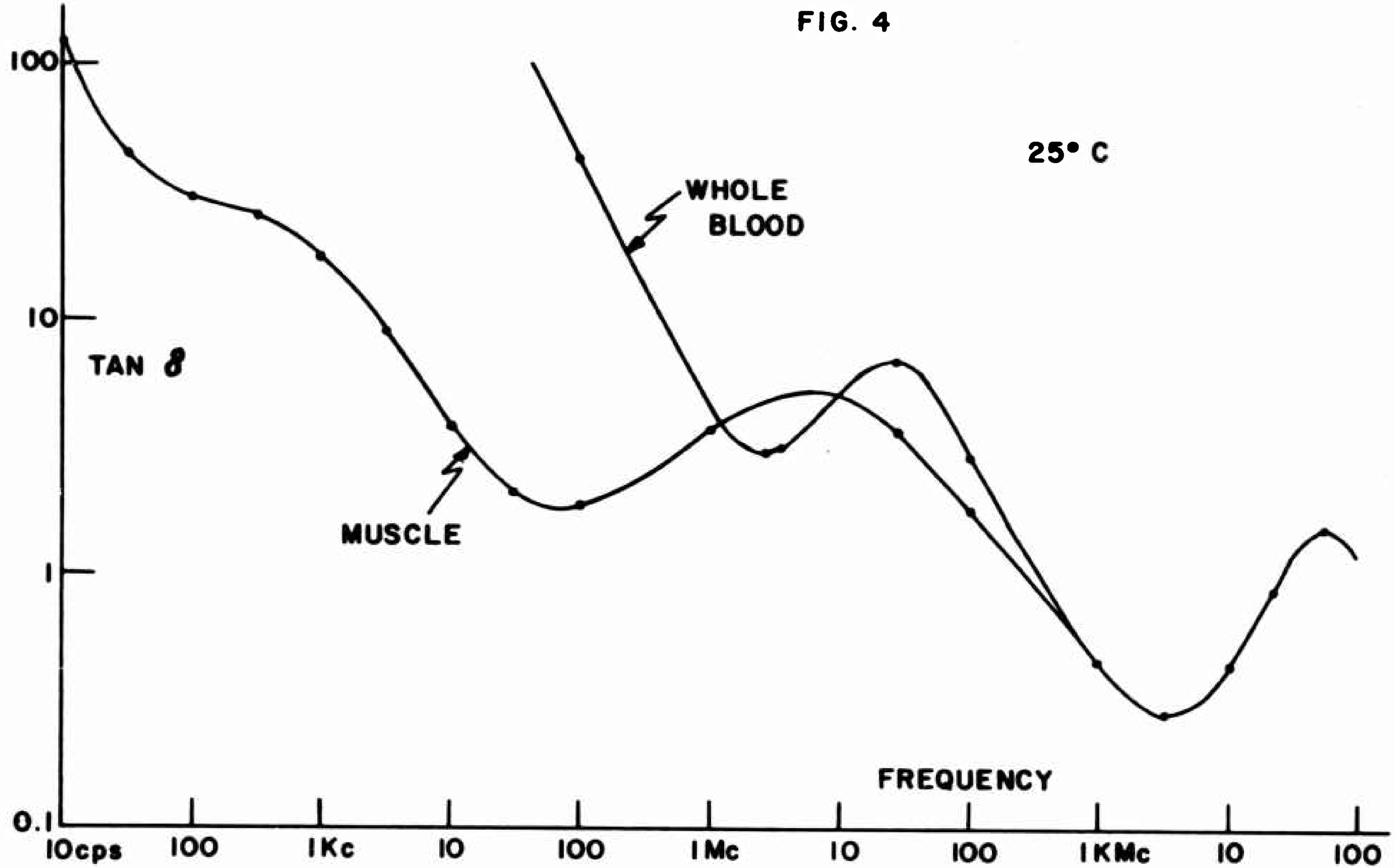

25° C
WHOLE BLOOD
MUSCLE
TAN δ
100
10
1
0.1
10cps
100
1Kc
10
100
1Mc
10
100
1KMc
10
100
FREQUENCY

TABLE 3

Tissue	Schwan and Kay	Burger and van Dongen	Rush, Abildskov, and McFee
Liver	840		700
Heart	965		ρ_h = 563
			ρ_l = 252
Lung	1120		2100
Fat	1500-5000		2500
Skeletal	965	ρ_h = 675	ρ_h = 2300
Muscle (human or dog)		ρ_l = 245	ρ_l = 150
Skeletal		ρ_h = 1800	
Muscle (rabbit)		ρ_l = 125	

Values ρ_h and ρ_l are high and low resistivities of anisotropic tissue. The skeletal muscle value given by Schwan and Kay was obtained with a small electrode providing a nearly spherical field. It is therefore a "random orientation" value and compares with the mean of the ρ_h and ρ_l values.

The power factor m varies somewhat with frequency and with other parameters such as electrode material. For platinum electrodes, for example, it varies slowly from 0.3 at 100 Hz to 0.5 at 100 KHz. The Figure 5 presents some typical values for polarization impedances.

Another important fact to be realized is that the electrode polarization impedance which is observed if an electrode is in contact with a biological fluid such as physiological saline solution is considerably smaller than that found if the electrode contacts tissue. In the latter case electrode polarization impedance values are approximately twice to three times higher than in the case of physiological saline soultion. This ratio of two to three applies for soft tissues with high water content such as muscle and body organs. No data exist for skin. But it appears possible that the aforementioned ratio is higher and variable for skin, depending on the skin's condition, particularly its "wetness" and preparation of its surface layers.

It appears that electrode polarization contributes but little to total observed body impedances above 100 KHz, the principal frequency range of interest in this study. Even between 10 and 100 KHz its contribution should be small. The validity of this statement may be recognized by using typical electrode impedance data at high frequencies as suggested by equations (11) and the data in Figure 5 and comparing them with body impedance data to be reported below. However, it must be stressed, that for rather small "point" contact electrodes, electrode impedances can become high even above 100 KHz. We shall assume that electrodes of a contact area of at least 1 mm^2 are of interest in this study and that therefore, electrode polarization contributions to the body's impedance are sufficiently small to warrant their neglect above 100 KHz.

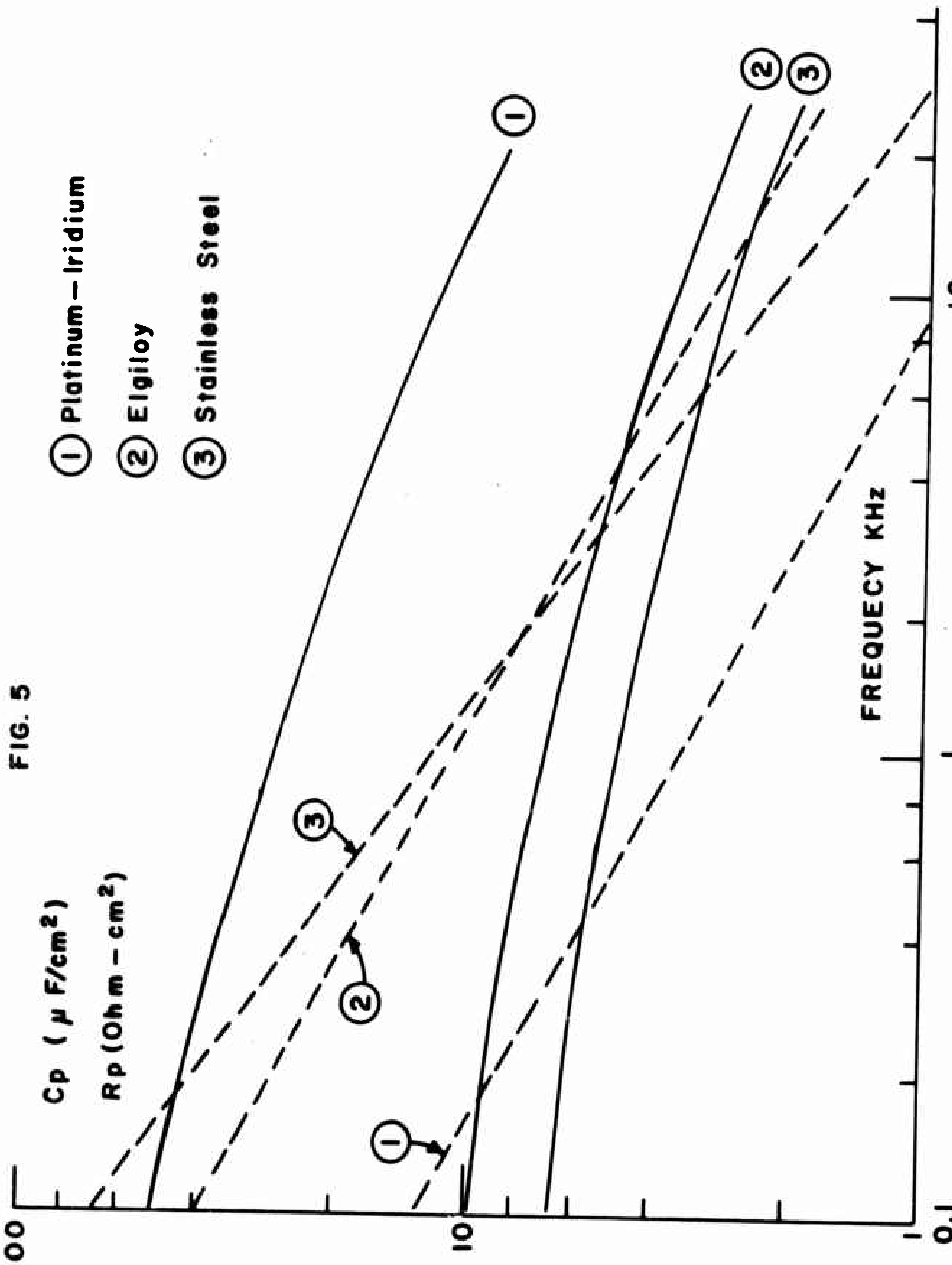
B. Skin impedance

Skin is a very heterogeneous tissue composed of different layers with different impedance characteristics. Its thickness varies between 2mm and 8mm between different parts of the body and, to a somewhat lesser extent, from individual to individual. The electrical properties of skin are highly sensitive to the skin's condition. The upper layers of skin can be quite dry. Under such conditions the skin resistance can be very high. However, if the upper skin layers are moist or even wet, the skin resistance can decrease very substantially.

Unfortunately, the determination of skin impedance properties is not easy. Its heterogenous structure makes it undesirable to specify specific impedance properties. However, it appears useful instead to consider skin impedances in terms of skin impedances per cm^2 skin surface area. The Table 4 lists some values for the skin surface impedance per cm^2 as function of frequency. The data change strongly with frequency and the magnitude of the phase angle is higher than for tissues, at least at the lower frequencies. It is considered quite possible that a good part of the rapid increase in quoted skin impedance values with decrease in frequency is simply due to electrode

Figure 5. Frequency dependence of polarization capacity C_p (solid lines) and resistance R_p (dashed lines) for platinum iridium, elgiloy and stainless steel electrodes (From Jaron, 1967). Typical electrode size 0.14 cm^2. However, data are presented in terms of values per cm^2. Note that Pt-Ir has a substantially higher C_p and lower R_p, i.e., a lower electrode impedance than the other materials.

FIG. 5



Cp (μ F/cm²)
Rp (Ohm - cm²)
① Platinum—Iridium
② Elgiloy
③ Stainless Steel
100
10
0.1
1
10
FREQUECY KHz

polarization, i.e., that the quoted values are the sum of skin and electrode impedance values. However, for frequencies in excess of 100 KHz the quoted values are primarily resistive in character and approach values of 100 to 500 Ohm-cm^2. These values will be of primary interest to us. Skin thickness varies between 2 and 8 mm, depending on body location and probably is not very different from 3 mm for most sites where electrodes might be placed. Hence the equivalent resistivity ρ of skin is about 3 times the surface value quoted in Table 4, i.e., close to 900 Ohm-cm^2 at 100 KHz. This value is about 2 times higher than that for muscle. A much smaller difference is indicated by skin data obtained above 100 MHz, i.e., at the other end of the frequency range of interest in this study (Table 2). While, unfortunately, no skin data between 0.2 MHz and 100 MHz appear to be available, the above reviewed data indicate that skin behaves above 100 KHz not drastically different from muscle from an electrical point of view. This fact enables us to treat skin alike to muscle and, therefore, simplifies our problem of body impedance value prediction considerably.

C. Factors affecting body impedance values

It is apparent from the above presented material that the body's total observed impedance is dependent on several additive components:

Electrode polarization impedance, Z_p
Skin impedance, Z_S
Body impedance, Z_B

It is the purpose of this study, to provide data on total body impedance values in the radio frequency range, i.e., about 100 KHz. At such frequencies, the electrode impedance can be neglected as discussed before. We have also concluded that the electrical properties of skin are not too different from those of muscle and that it therefore is justified to replace skin by muscle.

The body's impedance Z_B in turn may be divided into two parts. The first part represents the impedance of the subcutaneous fat layer Z_F, which is situated between skin and the deeper body tissues of high water content. The second part is the impedance Z_T of the body tissues, which are located beneath the subcutaneous fat layer and is usually primarily composed of muscular and organ tissues and bone. We may therefore write for the total body impedance Z the following equation

$$Z = Z_p + Z_S + Z_B \tag{13}$$

where Z_p and Z_S can be neglected for frequencies above 100 KHz and where

$$Z_B = Z_F + Z_T \tag{14}$$

The subcutaneous fat layer varies of course considerably from person to person and from one part of the body to another and it will be difficult

TABLE 4

Typical surface skin impedance values as function of frequency

Frequency KHz	Surface Impedance Impedance Magnitude	Impedance Phase Angle ϕ
1	14,000 Ohm-cm^2	
5	3,000	-70°
10	1,800	-65°
20	1,000	-55°
50	500	-30°
100	300	-20°
200	250	-10°

The impedance phase angle ϕ is defined by $\tan \phi = X/R$ where the impedance equation $Z = R + j X$ in turn defines resistive and reactive components R and X. The admittance phase angle is given by $\tan \delta = \kappa/\omega\varepsilon\varepsilon_0$. Hence, $\tan \phi = -1/\tan \delta$ or $\phi = -(\pi/2 - \delta)$. The data presented have been reported by Vransky and Emanuilov. The impedance magnitude is in the range indicated by Kinnen's admittance values at 100 KHz. However, the phase angles quoted by Kinnen are surprisingly higher and perhaps subject to inquiry.

to take it precisely into account. The contribution of Z_T to the body's impedance depends on the one hand on its blood content and on the other on the amount of space which is taken by bone, a comparatively non-conductive material. The effect of blood is noticeable at frequencies much below 100 KHz. As mentioned before, it may be neglected above 100 KHz.

For electrodes whose diameter is larger than or comparable to skin thickness and subcutaneous fat layer thickness, the fat layer impedance Z_F may be estimated by

$$Z_F = \rho_F\, d/A \qquad (15)$$

where d is the thickness of the subcutaneous fat layer and A the electrode area. For most electrode locations of interest, the subcutaneous fat layer is sufficiently small so that the assumptions underlying equation (15) appear reasonable. However, for electrode placements on the abdominal area, subcutaneous fat layer thickness values in excess of one inch are possible. Even in this case the equation (15) may provide an order of magnitude estimate. Its application and introduction of the specific impedance values of fat as given in Table 1 indicates that in this case very large body impedance values are possible. The "deep tissue impedance" Z_T in equation (14) is determined by electrode configuration, specific impedance data of the tissues found inside the body and the geometric arrangement of various tissues passed by the current. The influence of electrode geometry will be discussed in the next section. Here we will address ourselves to the question: What specific impedance values are appropriate? As shown in the tables of specific impedance data, all body tissues of high water content have comparable properties. An exception to this rule is bone, whose impedance is rather high. We shall assume that the effective specific impedance of soft tissues surrounding bone can be presented by the mixture equation

$$\frac{1}{\rho_T} = \frac{1 - V}{\rho_H} + \frac{V}{\rho_L} \qquad (16)$$

where ρ_T the effective specific impedance of the tissues beneath the subcutaneous fat layer, ρ_H that of muscle and other tissues of high water content, ρ_L that of bone and V the volume fraction occupied by bone. Since the specific impedance of bone, ρ_L is high in comparison with ρ_H, the approximation

$$\rho_T = \rho_H/(1-V) \qquad (17)$$

is indicated. The mixture equation (16) will surely deviate from whatever appropriate mixture formula may apply under a given set of

circumstances. But the dielectric theory of mixtures shows that the error of equation (16) is usually not large. It should be noted also, that V is the volume fraction of bone and does not necessarily include the rather well conducting bone marrow contained by bone. Hence, V is significantly smaller than the volume fraction taken by bone and its contained marrow. The error resulting from assuming $V = 0$ is therefore small in all cases where electrodes are not immediately placed very close to bone.

In conclusion then it may be stated that the body impedance characteristics include a highly variable subcutaneous fat impedance element (equation 15) and another tissue element whose specific impedance is given by equation (17).

IV. BODY IMPEDANCE VALUES

The following two cases will be discussed since they are of primary interest. In one case the electrode surfaces are large in comparison with the limb cross section, in the other they are small.

A. Large electrodes

Quite obviously it is not possible to attach to parts of the body, such as the trunk, or the limbs or even the fingers, electrodes in a manner as indicated in Figure 1a. However, it is possible to surround limbs with band electrodes of sufficient width, so that in effect, a field configuration exists similar to that indicated in Figure 1a. To this end, one has to merely assure oneself that the area of the band electrodes is at least as large as the cross section of the limb under consideration. In this case the body impedance contribution from electrode impedance, skin impedance and, in most cases even subcutaneous fat is not pronounced and equation (13) reduces to

$$Z = Z_B = \frac{\rho_H}{1-V}\,\frac{d}{A} \tag{18}$$

with due consideration of equations (2), (10), (15) and (17) and where d distance between band electrodes, A limb cross section and V relative bone volume.

In many cases it will be of no interest to consider electrodes which are as large as specified above. In these cases, therefore, the considerations of the next section are appropriate.

B. Smaller electrodes

If the electrode area is smaller than the cross section of the limb to which the electrode is attached, the impedance contribution near the electrode is large. In this case the equations (3), (4) and (6) are indicated, where the specific resistance $\rho = 1/\kappa$ is some average of the

specific resistances of skin, subcutaneous fat and tissues of high water content and bone since the current passes through skin, subcutaneous fat and the more deeply placed body tissues. The skin impedance is obtained by dividing the skin impedance value per cm^2 by the electrode area, i.e., equal to about $100/A(cm^2)$ Ohm.* The effect of bone may be considered as indicated by equation (17). In view of the fact that variability of ρ from one type of soft tissue to another appears to be always within a factor of less than ten, it is appropriate to set the effective value of ρ somewhat, say twice higher than that of the specific resistance of tissues with high water content such as muscle. One will probably obtain in this manner an equation which is in most cases accurate within a factor of two. Hence, for the total body impedance

$$Z_{total}\ (\mathrm{Ohm}) = \frac{100}{\pi r_1^2} + \frac{100}{\pi r_2^2} + \frac{2\rho\,(\mathrm{Muscle})}{1 - V} \cdot \frac{1}{2\pi}\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad (19)$$

or, in view of the approximate nature of this expression and using ρ (Muscle) = 200 Ohm-cm

$$Z_{total} = \frac{30}{r^2} + \frac{60}{1-V}\,\frac{1}{r} \qquad (20)$$

or

$$Z_{total} = \frac{100}{A} \quad \frac{100}{(1-V)}\,\frac{1}{\sqrt{A}} \qquad (21)$$

where r is the smaller of the two electrodes of radius r_1 and r_2 (assumed to be rather unequal) and A the corresponding electrode area. The value for Z_{total} may be as much as double as large if the two electrodes are of comparable size. The first term in equations (20) and (21) is usually small, unless the electrodes are small in area. However, for electrode areas of less than 1 cm^2 the skin impedance contribution becomes larger than that of the body.

C. Comparison of calculated and measured impedance values

Only very few total body impedance values have been quoted in the literature. Table 5 quotes values which the author has found in an older German text (Vilbig, 1939). These values are compared with

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* Table 4 gives a value of 250 Ohm-cm^2 at 200 KHz, Table 2 a value of 120-140 Ohm-cm for the specific resistance or 50 for the surface resistance, assuming a skin thickness of 4 mm. Since the skin impedance often does not contribute the major part of the body impedance, it appears that a geometric mean of 100 Ohm-cm^2 is justified.

the values deduced from equations (18) and (19), where the choice of equation was dictated by its appropriateness in accordance with the principals indicated before. The effect of V was neglected since it really represents the relative volume of bone exclusive of its inner comparatively conducting marrow and since this relative bone volume is usually much less than 50%. The comparison of experimental and calculated values indicates that the derived formulas give body impedance values accurate within a factor of two. Additional confirmation was obtained in some preliminary measurements taken at the Naval Weapons Laboratory in 1968 (See Appendix A).

More recent body impedance data are available at frequencies below 1 KHz (Sinbel, 1966). Since part of these data below 1 KHz are subject to inquiry on account of electrode polarization errors, we have only considered 1 KHz data in detail. These data may be summarized by stating the following impedance magnitudes:

Left arm	400 - 460 Ohm
Right arm	370 - 490
Left leg	370 - 490
Right leg	360 - 490
Trunk	30

The following composite values were measured:

Arm to arm	1500
Right arm to left leg	900

The arm to arm value is about 3-1/2 times higher than that reported in Table 5, reflecting appropriately the frequency dependence anticipated in Section 4 below. The limb data are also about double to three times as high as the theoretical values quoted in the lower part of Table 5. The right arm to left leg-value above is again about 3-1/2 times higher than the value in Table 5. The trunk value is about 1-1/2 times higher than the 1 MHz thorax value in Table 5. Clearly, the values given by Sinbel, those given in Table 5, and those calculated from the equations derived in this report are consistent if adequate allowance is made for the frequency dependence of the specific impedance of body tissues.

D. Frequency dependence and phase angle of body impedance

A specific impedance of 200 Ohm-cm was assumed for body tissues of high water content in equation (20). This value is fairly typical for the frequency range from about 0.1 to 1 MHz. As the frequency increases this value drops to about 100 Ohm-cm near 100 MHz. It increases as the frequency is lowered to a value somewhere between 500 and 1000 Ohm-cm at 1 KHz. Thus it may be anticipated that body tissue impedance values are about three or four times higher at 1 KHz and twice lower at 100 MHz than those at 100 KHz or 1 MHz. Clearly, while there is a marked frequency dependence, it is fairly gradual. Variability in impedance values due to its frequency dependence is small in comparison with the uncertainties inherent in the assumptions which led to the equations derived.

TABLE 5

Electrode Location	Electrode Area	Resistance (Ohms) 0.375 MHz	1 MHz	Calculated Value
Hand to hand	90 cm^2	475	460	400 (d = 100, A = 50)
One finger to other arm	10 65	500	470	500 (d = 50, A = 2)
Across left arm 20 cm from hand	32 32	34	21	42
Across elbow joint	32 32	37	21	42
Across shoulder joint	32 32	47	31	42
Across neck, side to side	32 32	36	18	42
Forehead to neck	32 32	82	57	42
Chest to back	150 150	31	20	18
Thorax, side to side	150 150	29	19	18
Right wrist to left leg	75 75	248	234	200* (d = 50, A = 50)
Left wrist to left leg	75 75	274	266	200* (d = 50, A = 50)

Body resistance values at 0.375 and 1 MHz. The electrode areas are listed in column 2. Column 4 lists calculated values using equations (18) and (19) and the quoted reasonable distance values d in cm and limb cross sections A in cm^2. The difference between the 0.375 and 1 MHz-values fluctuates only between 10 and 30 Ohms, while the resistance fluctuates by a factor of ten. This may be explained in good part by variation in skin impedance between the two frequencies quoted. Phase angles are sufficiently small, so that resistance and magnitude of impedance values are nearly identical. Measured phase angles agree with those calculated from Figure 4.

* These values consider only the impedance of one arm, since trunk and leg add to a lesser extent.

Inspection of the Tables 1 and 2 indicate that the electrical phase angle of tissue impedance varies much less with large variation in water content than does either dielectric constant or resistivity. Thus it appears warranted to equate the body's phase angle with that of muscular tissue. Tan δ varies according to Figure 4 between 1.5 and 5 in the range from 10 KHz to 100 MHz. Hence the phase angle δ should be between 55° and 80° and its complement, the tissue impedance phase angle ϕ, between -10° and -35°.

VI. CONCLUSIONS

The body's impedance is highly variable, depending on electrode location, electrode size, frequency and the nature of the tissues beneath the electrode. However, at frequencies above 100 KHz complexities reduce significantly since electrode polarization phenomena can be neglected in all cases where the electrode is at least 1 mm^2 in area and the skin impedance is less variable than at lower frequencies. At frequencies above 100 KHz it has been therefore possible to derive equations which are useful in the estimation of body impedances. Impedance magnitudes predicted by these equations compare well with a few values quoted in the literature and experiments and range from 20 to 500 Ohms, i.e., over a range of almost two decades depending on circumstances. The body impedance's phase angle should be between the phase angle values for skin and body tissue and has no great effect on the magnitude of the impedance.

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APPENDIX A

SOME PRELIMINARY BODY IMPEDANCE MEASUREMENTS

APPENDIX A

Some preliminary body impedance measurements.

Frequency range: 1 to 100 MHz

Electrodes: 1 cm long, 1 mm diameter, other electrode large round contact.

Material: One finger held the small electrode, while part of the same hand rested against ground.

Impedance amplitude: 1.5 to 0.6 K Ohm as frequency increased from 1 to 100 MHz.

Impedance phase angle: Between 20° and 40°

Comments: If the finger was wetted, the impedance values were somewhat lower, if the impedance was taken between finger and other hand, some 20% higher.

Calculations: Since one electrode is small and the electrodes of greatly unequal size, equation (21) appears indicated. The electrode area is $A = 2\pi r = 0.31$ cm^2. It is judged that about 1/2 or 1/3 of the total electrode area was touched. Hence, $A = 0.15$ cm^2. Hence, from equation (21) Z equal to 700 Ohm if $V = 0$ is assumed or 1100 if $V = 0.5$ is assumed. The calculated values compare with the impedance amplitude range measured. The first term of equation (21) is higher than the second since A is small. Hence, skin impedance primarily contributes to the measured impedance.

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13. ABSTRACT

The object of this report is to establish the theoretical range of radio frequency impedance of the human body in the 1 - 30 MHz range. The report defines whole body rf impedance, summarized available specific tissue impedance data, and predicts likely values of total body impedance for various electrode sizes and locations from known specific tissue data and skin impedance. The report also discusses the relation of body impedance to electrode impedance, skin impedance and specific body impedance.

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